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Abstract: Der Unterwuchs als Teil der Waldstruktur hat eine wichtige Funktion im Hinblick auf die Dynamik der Waldentwicklung. Allerdings ist die Charakterisierung des Unterwuchses mittels Fernerkundungsmethoden problematisch, da die Vegetationsdichte eine Erfassung der vertikalen Struktur stark limitiert. Unter Verwendung von flugzeuggestütztem, multi-temporalen Laserscanning ist es möglich, den Unterwuchs in einem dichten Laubwald zu detektieren und zu charakterisieren. Basierend auf den geometrischen Informationen der Laser-Punktwolke und den zugehörigen full-waveform Charakteristiken wurden folgende Unterwuchsklassen abgeleitet: vegetationsfreie Flächen, Streu, Unterwuchs < 0.5 m, Unterwuchs 0.5-3 m und Verjüngung > 3 m. Für die Validierung wurde sowohl terrestrisches Laserscanning als auch eine umfangreiche Feldmessung entsprechend dem VALERI Ansatzes verwendet. Die Detektion des Unterwuchses erfolgte mit einer Genauigkeit von 78%; die Klassifikation erreichte eine Genauigkeit von 64%.

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Characterization of forest understory using multi-temporal full-waveform airborne laser scanning

REIK LEITERER¹, FELIX MORS DORF¹ & MICHAEL E. SCHAEPMAN¹

Zusammenfassung: Der Unterwuchs als Teil der Waldstruktur hat eine wichtige Funktion im Hinblick auf die Dynamik der Waldentwicklung. Allerdings ist die Charakterisierung des Unterwuchses mittels Fernerkundungsmethoden problematisch, da die Vegetationsdichte eine Erfassung der vertikalen Struktur stark limitiert. Unter Verwendung von flugzeuggestütztem, multi-temporalen Laserscanning ist es möglich, den Unterwuchs in einem dichten Laubwald zu detektieren und zu charakterisieren. Basierend auf den geometrischen Informationen der Laser-Punktwolke und den zugehörigen full-waveform Charakteristiken wurden folgende Unterwuchsklassen abgeleitet: vegetationsfreie Flächen, Streu, Unterwuchs < 0.5 m, Unterwuchs 0.5-3 m und Verjüngung > 3 m. Für die Validierung wurde sowohl terrestrisches Laserscanning als auch eine umfangreiche Feldmessung entsprechend dem VALERI Ansatzes verwendet. Die Detektion des Unterwuchses erfolgte mit einer Genauigkeit von 78%; die Klassifikation erreichte eine Genauigkeit von 64%.

1 Introduction

Forests play a pivotal role in the global biogeochemical and -physical cycles and provide a range of essential goods and services (e.g. maintenance of biodiversity, soil and water conservation, wood fuel) [ROSS 2011, DE GROOT *et al.* 2002]. Particularly the forest structure influences the fluxes of energy and matter between the atmosphere and forests and can serve as a proxy to determine forest stand resistance to disturbances or to estimate the conservation potential for biodiversity [KAYES & TINKER 2012, NADKARNI *et al.* 2008, XUE *et al.* 2011].

Understory as part of the forest structure plays a crucial role in forest ecosystems (e.g. limitation for establishment, important habitat component) but is difficult to assess. Conventional fieldwork is time-consuming, often subjective and mostly limited in its spatial extent [FOODY 2010, HAARA & LESKINEN 2009], whereas traditional remote sensing methods can only provide information about the top layer of the canopy [JONES *et al.* 2012; HALL *et al.* 2011]. Airborne laser scanning (ALS) systems have shown the potential to provide explicit vertical information about the forest structure due to the canopy penetration of the emitted signal [KAARTINEN *et al.* 2012, LINDBERG & HOLLAUS 2012, LEEUWEN & NIEUWENHUIS 2010]. However, most of the existing approaches to characterize forest understory based on ALS data focus on the detection and description of understory trees only [KORPELA *et al.* 2012, MALTAMO 2005, HIRATA *et al.* 2003] or were applied in areas with mainly open forest, enabling high canopy penetration rates of laser pulses [FERRAZ *et al.* 2012, MORS DORF *et al.* 2010, KORPELA 2008]. In dense deciduous forests, particularly under foliate conditions, penetration of the laser signal to lower vegetation layers (understory) is strongly limited. In such cases acquisition under defoliated condition is essential to detect the understory, whereas the leaf-on acquisition can still provide significant information to characterize the detected understory, e.g. based on the light availability.

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2 Study area and data

The study site is the Laegeren mountain (forming part of the Swiss Jura; 47°28'N, 8°21'E) and is dominated by steep slopes. The semi-natural and dense, deciduous-dominated forest stand is characterized by a high diversity of species (mostly *Fagus sylvatica* (L.), *Picea abies* (L.) Karst, and *Fraxinus excelsior* (L.)), age (55-160 years), and diameter distribution (7-120 cm) [EUGSTER *et al.* 2007]. The data acquisition was performed under foliated (or leaf-on) conditions using a RIEGL LMS-Q680i sensor and under defoliated conditions (or leaf-off) using a RIEGL LMS-Q560 sensor. Sensor specifications and settings used in this study are summarized in Table 1 (for more details see WAGNER *et al.* [2008] and the technical sensor documentation as provided by RIEGL [RIEGL 2012]).

Table 1: Sensor specifications and settings of the RIEGL LMS-Q560 and LMS-Q680i.

	LMS-Q560	LMS-Q680i
pulse repetition rate [Hz]	200 000 Hz	
scan angle [deg]	± 15 deg	
mean operating altitude above ground [m]	500 m	
mean point density for the area of interest [pts/m ²]	~ 20	~ 40
date of acquisition	10.04.2010	01.08.2010

For the study area, an extensive set of ground based reference data is available, mainly measured during field campaigns in September 2011: Digital Hemispherical Photography's, Terrestrial Laser Scanning (TLS) using an Z+F IMAGER 5006, and extensive field measurements of ground cover and understory vegetation. Additional, soil distribution maps and a species classification were available. All field measurements were geo-referenced and co-registered based on the terrestrial land surveying using a total station and a differential GPS system.

3 Method

The understory detection and characterization consists of three methods: data pre-processing, tree delineation within the understory layer for trees > 3 m; and the classification of understory vegetation/ground cover ≤ 3 m.

3.1 Data pre-processing

In comparison to discrete laser systems, full-waveform systems enable the approximation of the entire backscattered signal by digitization, which facilitates the extraction of additional features for each reflecting object within the ALS footprint [MALLET & BRETAR 2009]. Gaussian pulse estimation [WAGNER *et al.* 2006] was applied in order to obtain representative echo descriptions, resulting in a point cloud with its basic and established geometrical characteristics of reflectors (range and echo types) as well as in a physical characterization of each reflecting object, including information such as amplitude, width and consequently intensity of each specific echo. First of all, we extracted ground returns from the point cloud using single and last echoes, their geometrical characteristics and the corresponding echo width information [MÜCKE *et al.* 2010].

To detect and filter remaining vegetation echoes, a new adaptive multi-scale filter algorithm based on the method by EVANS & HUDAK (2007) was developed. As initial part of the filtering, a kernel based query was applied to the ground echoes to identify areas with high deviations in height values ($\geq 100\%$ slope). Within the identified areas, a combination of optimized spline function analyses and a scale dependent (using a 3x3 and/or 5x5 kernel) multi-point triangulation was applied to exclude non-ground echoes from the point cloud. The usage of a spline function approach allows for a reliable distinction between height deviations caused by steep terrain and the more likely less continuous height deviations caused by artificial objects or dense vegetation. Finally, the remaining points were interpolated to a 1x1 m digital terrain model (DTM) based on ordinary kriging. A 1x1 m digital surface model (DSM) was processed using the first echo reflections and their corresponding echo width information. The canopy height model (CHM) was calculated as a subtraction of the DTM from the DSM. For each echo of the point cloud we were now able to determine the height above ground as well as the corresponding DTM, DSM and CHM values (Figure 1). Similar to the processing of the ALS data, we calculated the height above ground for each point of the TLS measurements.

3.2 Understory tree delineation

To identify understory trees, we applied an iterative, three-dimensional grayscale dilation of the point cloud using an oblate spheroid-shaped structuring element (minor axis = 1.5 m, major axis = 5 m) [ADAMS 1993]. A local maximum is assumed to belong to an understory tree, if it is > 3 m above ground and at least 3 m below the specific canopy height at this position. The resulting local maxima were used as initial seed-points for a k-means clustering analysis, which segments the point cloud into clusters of ALS returns presumably belonging to one tree (Figure 2). An Euclidean metric is used to compute distances in the three-dimensional feature space. As such a combination favors ball shaped clusters in a three-dimensional feature space, a re-scaling of the height values was applied to account for aspect ratio of features in the point cloud. Finally, we computed the alpha shapes of the resulting individual clusters of points, which facilitate the derivation of additional variables at the crown level [VAUHKONEN *et al.* 2009].

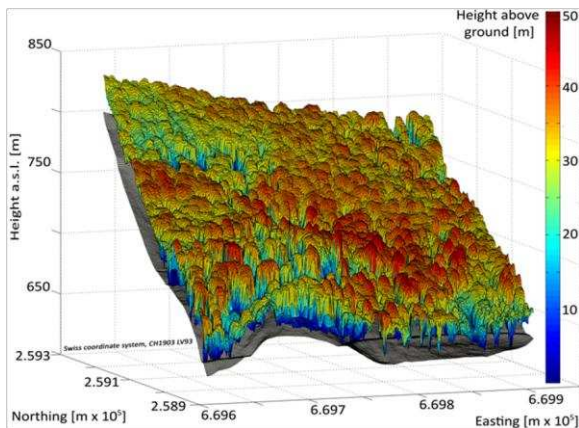


Figure 1: Digital terrain model (in gray) and digital surface model colored with the canopy height information for the area of interest.

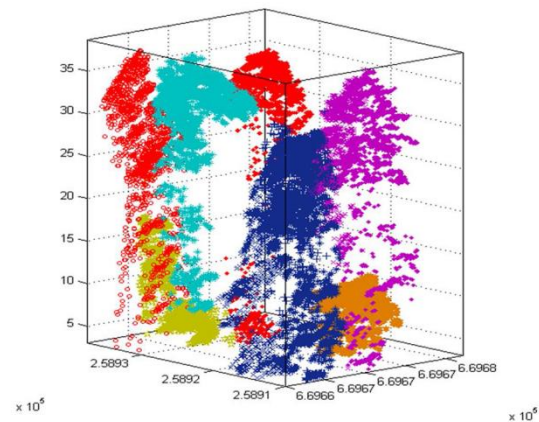


Figure 2: Example of the point cloud segmentation. The green and orange colored point clusters represent detected understory trees.

3.3 Classification of understory vegetation and ground cover

The ground properties and understory vegetation was evaluated on a 1x1 m grid size. For each grid cell the vertical column was subdivided into boxes with a vertical extent of 0.25 m. Within these specific boxes we calculated the percentage amount of echoes, the leaf-on/leaf-off variation in the point cloud and common quantitative statistical measures for the full-waveform variables (e.g. frequency distributions, statistical dispersion and central tendency). The classes ‘understory < 0.5 m’ and ‘understory 0.5-3 m’ were derived from the echo distribution contained in the boxes of the corresponding height ranges. Considering vertical distribution of scattering objects within one footprint, echoes with larger widths were represented as line segments, oriented in three-dimensional space according to the scan angle. If a line segment (or a part of it) is contained in a box, it is counted as an echo. A box is labeled as vegetation, if the percentage of echoes within the box is at least 5% of all echoes in the height range 0-3 m (terrain corrected). Grid cells are defined as ‘non-vegetated areas’ or ‘litter’, if > 95% of all echoes in the range 0-3 m are located in the 0-0.25 m box and > 95% of the echoes have small echo widths and high amplitude values. In addition, the statistical dispersion of the echo types was used as an indicator for light availability, which should indicate the probability of the occurrence of low height vegetation. To distinguish between ‘non-vegetated areas’ and ‘litter’, we used a combination of the frequency distribution and central tendency of the echo types, echo widths, and amplitude values.

4 Results and discussion

Figure 3 shows the result of the tree delineation and the understory/ground cover classification (1x1 m grid).

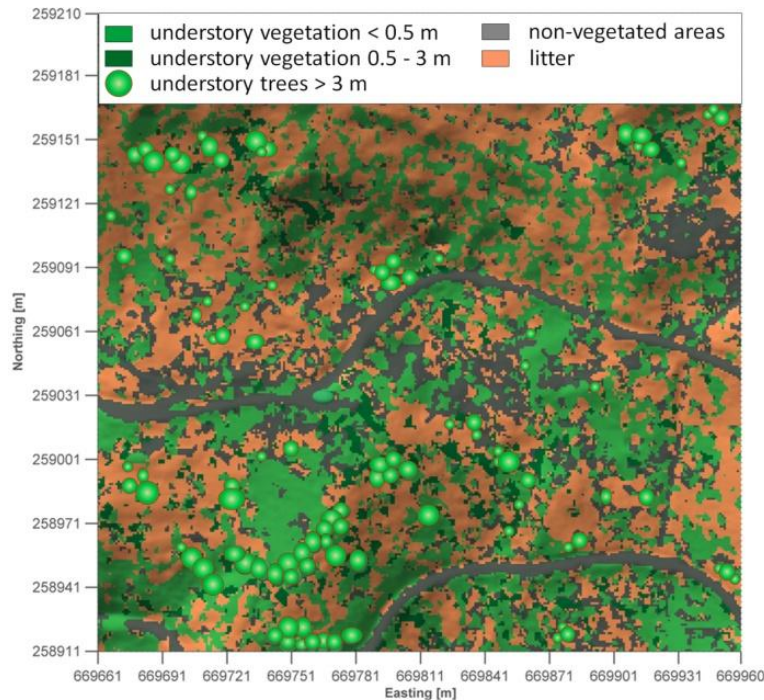


Figure 3: Understory tree delineation and classification result for understory vegetation and ground cover.

The validation of the understory tree detection was based on TLS measurements within two 40x40 m plots and the stratified field measurements outside these areas. The commission and omission error for the delineation is 26.7% and 39.8%, respectively. The commission errors are mainly caused by the detection of crown parts belonging to low reaching crowns of dominant trees, whereby the omission errors have been caused by the large amount of clustered and multi-stemmed trees due to former coppicing activities [VAN CALSTER *et al.* 2008]. These errors correspond to the findings of existing approaches [e.g. KAARTINEN *et al.* 2012, FERRAZ *et al.* 2012] and point out the general limitations for understory tree detection even if multi-temporal ALS data with very high point densities are available. The classification of the understory and the ground cover was compared to a reference data set derived from the TLS data, field measurements and the available plant sociology classification. Utilizing the resulting confusion matrix, we calculated the common statistics metrics overall accuracy, users/producers accuracy and Cohen's kappa coefficient [LIU *et al.* 2007] (Table 2).

Table 2: Confusion matrix for the understory/ground cover classification.

Classification Reference	Understory 0.5-3 m	Understory < 0.5 m	Litter	Non-vegetated areas	Producer's accuracy [%]
Understory 0.5-3 m	76	16	1	0	81.72
Understory < 0.5 m	21	49	6	4	61.25
Litter	4	12	39	21	51.31
Non-vegetated areas	2	7	22	44	58.67
User's [%]	73.77	58.33	57.35	63.77	
Overall Accuracy [%]: 64.19			Cohen's Kappa: 0.52		

As can be seen from the confusion matrix, we achieved an overall accuracy of ~ 64% and a detection rate of the understory vegetation ≤ 3 m of ~ 89%. The highest degree of class overlap exists for the 'litter' and 'non-vegetated' classes, mainly caused by the similarity of the reflection properties of bare soil and leaf litter. Considering the percentage amount of 'understory trees > 3 m' on the total understory and the related detection rate, we end up with a detection rate for the total understory of 78%.

5 Conclusion

In this study, we present a robust and transferable method to provide a detailed characterization of understory composition and ground cover in a dense, deciduous forest. The validation shows that the detection and characterization of understory/ground cover can be achieved with high accuracy, although the delineation of understory trees is limited by the specific stand characteristics of our study site (e.g. former coppice management, multi-layered crowns). For the land cover classes 'non-vegetated areas', 'litter', 'understory < 0.5 m', and 'understory 0.5-3 m', we achieved a detection rate of 89% for the occurrence of understory and an overall accuracy of 64% for the understory type classification. We conclude that it is possible to detect and characterize forest understory robustly with our method based on ALS data; however, the availability of leaf-on/ leaf-off data with a high point density is indispensable.

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